

Inertial MEMS System Applications

N. Barbour, R. Hopkins, A. Kourepinis, P. Ward

The Charles Stark Draper Laboratory (P-4993)

555 Technology Square

Cambridge, MA 02139-3563

USA

email: nbarbour@draper.com

ABSTRACT

The performance of MEMS inertial technology has evolved from automotive quality to that approaching tactical-grade quality (1 deg/h, 1 mg). This evolution is a direct result of advances made in the key technology areas driven by gun-launched projectile requirements. The application of silicon MEMS inertial technology to competent munitions efforts began in the early 1990s. Initially, gun hardness was demonstrated at the sensor level, although the bias-and-scale factor of these gyros and accelerometers was mostly suitable for automotive or commercial use. Subsequently, development programs were initiated to develop gun-hard inertial systems with greatly improved sensor performance, and with a goal of low production cost.

This paper discusses the evolution of low-cost MEMS inertial system technology development for guided projectile INS/GPS systems and high performance IMUs. The evolution in sensors and packaging to realize performance improvement and system size reduction are presented. Recent data from the culmination of a three-year effort to develop an 8 cu in IMU are summarized, and represent the highest performance to date for an all-silicon IMU. Further investments in Silicon MEMS systems will ultimately realize IMUs that are smaller (less than 2 in³ (33 cc), higher performing (1 deg/h and less than 1 mg), and lower in cost (less than \$1200 per IMU and \$1500 per INS/GPS) than is achievable in any competing technology.

1. INTRODUCTION

The performance levels of MEMS inertial technology is approaching tactical-grade quality (1 deg/h, 1 mg). This evolution is a direct result of advances made in the key technology areas driven by gun-launched projectile requirements. These applications have a unique combination of requirements including, performance over temperature, high-g launch survivability, fast initialization and startup, small size, and relatively low overall system cost. The application of silicon MEMS inertial technology to competent munitions efforts began in the early 1990s. Initially, gun hardness was demonstrated at the sensor level, although the bias and scale factor of these gyros and accelerometers were mostly suitable for automotive or commercial use. Subsequently, development programs were initiated to develop gun-hard inertial systems with greatly improved sensor performance, and with a goal of low production cost (Refs 1- 6). This paper discusses the evolution of low-cost MEMS inertial systems through the Extended Range Guided Munition (ERGM) Demonstration, the Competent Munitions Advanced Technology Demonstration (CMATD), and the DARPA Micromechanical Inertial Measurement Unit (MMIMU) programs. ERGM Demonstration and CMATD involved guided projectile tests of MEMS INS/GPS systems, whereas MMIMU concentrated on the development of a high-performance MEMS IMU. Another important gun-hard technology development program is the Low Cost Guidance Electronics Unit (LCGEU) which utilized COTS MEMS in a modular INS/GPS designed to be robust to GPS jamming (Ref 7). The culmination of much of the technology

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE MAR 2010	2. REPORT TYPE N/A	3. DATES COVERED -		
4. TITLE AND SUBTITLE Inertial MEMS System Applications		5a. CONTRACT NUMBER		
		5b. GRANT NUMBER		
		5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S)		5d. PROJECT NUMBER		
		5e. TASK NUMBER		
		5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Charles Stark Draper Laboratory (P-4994) Cambridge, MA 02139 USA		8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)		
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited				
13. SUPPLEMENTARY NOTES See also ADA569232. Low-Cost Navigation Sensors and Integration Technology (Capteurs de navigation a faible cout et technologie d'integration) RTO-EN-SET-116(2010)				
14. ABSTRACT The performance of MEMS inertial technology has evolved from automotive quality to that approaching tactical-grade quality (1 deg/h, 1 mg). This evolution is a direct result of advances made in the key technology areas driven by gun-launched projectile requirements. The application of silicon MEMS inertial technology to competent munitions efforts began in the early 1990s. Initially, gun hardness was demonstrated at the sensor level, although the bias-and-scale factor of these gyros and accelerometers was mostly suitable for automotive or commercial use. Subsequently, development programs were initiated to develop gun-hard inertial systems with greatly improved sensor performance, and with a goal of low production cost. This paper discusses the evolution of low-cost MEMS inertial system technology development for guided projectile INS/GPS systems and high performance IMUs. The evolution in sensors and packaging to realize performance improvement and system size reduction are presented. Recent data from the culmination of a three-year effort to develop an 8 cu in IMU are summarized, and represent the highest performance to date for an all-silicon IMU. Further investments in Silicon MEMS systems will ultimately realize IMUs that are smaller (less than 2 in³ (33 cc), higher performing (1 deg/h and less than 1 mg), and lower in cost (less than \$1200 per IMU and \$1500 per INS/GPS) than is achievable in any competing technology.				
15. SUBJECT TERMS				
16. SECURITY CLASSIFICATION OF: a. REPORT unclassified		17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 14	19a. NAME OF RESPONSIBLE PERSON
b. ABSTRACT unclassified				

Inertial MEMS System Applications

evolution will be in the recently started Common Guidance IMU (CGIMU) program, which has the goal of being incorporated across multiple projectile platforms. Figure 1 provides a top-level description of the technology roadmap for the ERGM, CMATD, MMIMU, LCGEU, and CGIMU systems.

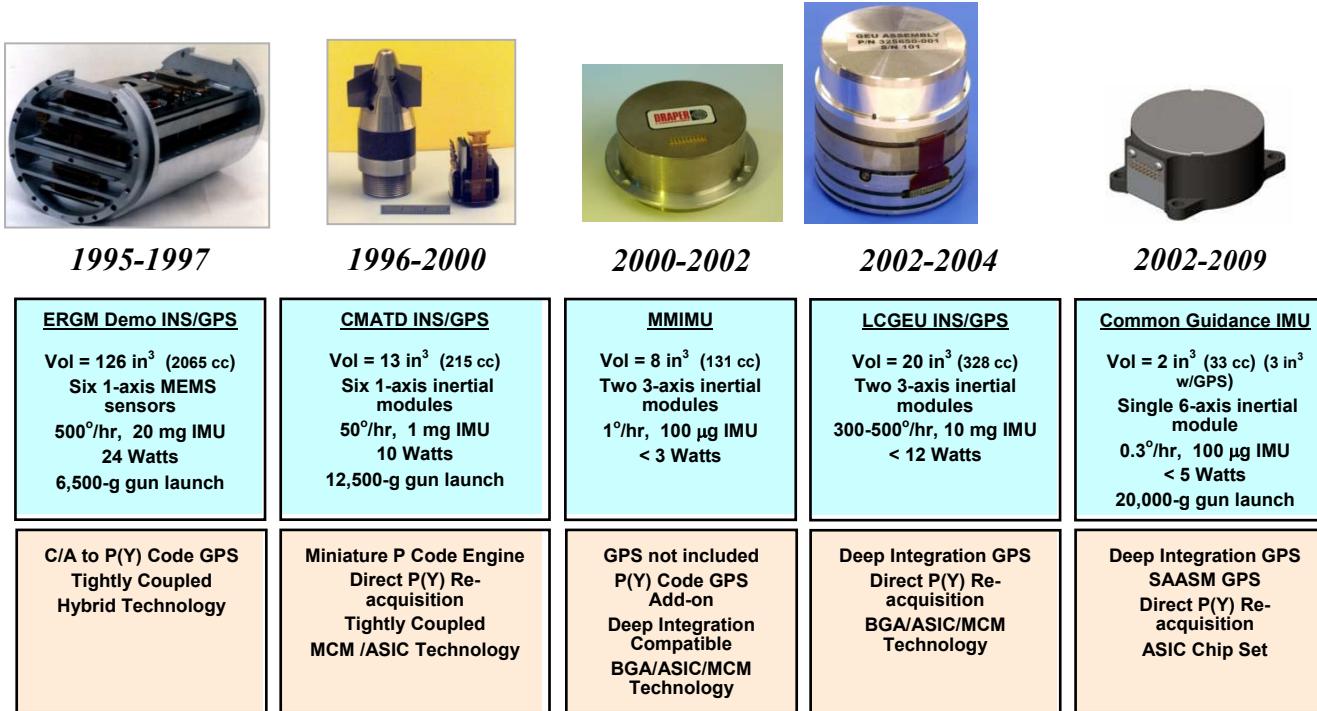


Figure 1. System Technology Roadmap

Table 1 shows typical environments for tank, artillery, missile, and mortar munitions.

Table 1. Munition Environments

	Units	Tank (120 mm)	Artillery (155 mm)	Missile	Mortar (4.2")
Launch Conditions					
-- Chamber Pressure	ksi	80	60		15
-- Max Axial Launch Acceleration	g	100K	20K	500	10K
-- Max Radial Launch Acceleration	g	10K	2K	50	1k
-- Angular Rotation In-Bore (Twist)	rev/cal	0	1/20	0	1/20
-- Motor/Propellant Temp	K	300	3000	3000	3000
-- Time In-Bore	ms	7-10	10-20		5
Flight Conditions					
-- Base Pressure	ksi	20	20	20	20
-- Max Axial Flight Accel (Drag)	g	-5	-10	-20	-5
-- Max Radial Flight Accel	g	0.50	0.50	2.00	1
-- Angle of Attack	degrees	±5	±15	±15	±15
-- Structural Vibrations	KHz	10	10	10	10
-- Roll Rate	Hz	0-60	100-300	0-60	0-130
-- Yaw/Pitch Rate	Hz	0-10	0-40	0-10	0-40
-- Time In-Flight	s	10	200	1000	30

Ref 8 Brown et al, "Strap-Down Micromechanical (MEMS) Sensors for High-G Munition Applications", IEEE Transactions on Magnetics, Jan 2001

2. GUN HARD MEMS IMU DEVELOPMENT – ERGM DEMONSTRATION, CMATD, MMIMU, LCGEU, CGIMU

2.1 ERGM Demonstration INS/GPS

In March 1995, the Naval Surface Fire Support branch initiated a proof-of-concept demonstration for the Extended-Range Guided Munition (ERGM). The ERGM Demonstration program was the first successful demonstration of a gun-launched MEMS-based INS/GPS system. The system consisted of a 126 in³ (2065 cc) avionics package containing a 6-degree-of-freedom MEMS inertial system, a Rockwell-Collins C/A-to-P(Y) code reacquisition GPS receiver with L1 tracking only, a TMS320C30 flight processor and power conversion and regulation electronics, which were sectionally mounted into a Deadeye Projectile.

The relatively generous volume of 126 in³ (2065 cc) allowed conservative, rugged packaging technologies to be used to meet the required survivability goals. Five PWBs were hard-mounted to rigid aluminum frames and bolted into a cylindrical housing with end plates that served as the primary load bearing structure. The sensors and their discrete electronics were packaged using thin-film hybrid MCM-C technology and mounted in bulky hermetic metal housings structurally bonded to standard PCBs. The ERGM Demonstration sensor electronics packaging appears in Figure 2.

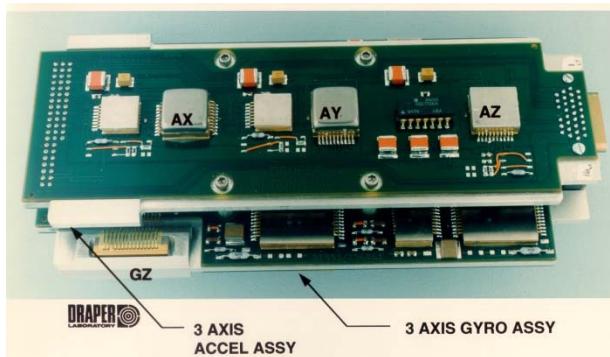


Figure 2. ERGM Demonstration Sensor Electronics Packaging

A photo of the first of three (November 1996 and two in April 1997) successful ERGM Demonstration test flights is shown in Figure 3. This effort first demonstrated successful reacquisition of GPS after gun launch and proved the survivability and ability of MEMS inertial components to operate after launch and accurately measure body rates and accelerations. The MEMS-based system was composed of repackaged automotive-grade inertial components (Draper Laboratory TFG gyros and pendulous accelerometers with uncompensated performance of 1,000 deg/hr and 50 mg) and was able to perform down-determination successfully and provide inputs for a full navigation solution.

2.2 CMATD INS/GPS

From March 1996 through February 2000, under funding from the Office of Naval Research, a series of three flight tests for the Competent Munitions Advanced Technology Demonstration (CMATD) Program was completed. The objective was to demonstrate MEMS-based guidance, navigation, and control (GN&C) within the fuze section of unguided artillery rounds. Figure 4 is a photo of the CMATD 5-inch (127 mm) projectile in-flight, 20 ms after the 6,500-g gun launch. The system GN&C is 13 in³ (215 cc) total, with 8 in³ (131 cc) for the G&N electronics. Although the MEMS gyros and accelerometers were similar to ERGM Demonstration, the CMATD sensor electronics were the first to be ASIC-based. This contributed to an order of magnitude improvement over ERGM Demonstration performance.



Figure 3. ERGM Demonstration Flight Test



Figure 4. CMATD Projectile in Flight

The volume constraint of 8 in³ (131 cc) for the electronics assembly was very aggressive, and is shown in Figure 5. This system consists of a flight computer module, three orthogonal accelerometer modules, three orthogonal gyroscope modules, a two-card GPS receiver, a TCXO clock board, and a voltage regulator card. Each of these assemblies is molded in epoxy and secured in a cavity of the projectile housing by wax and glass bead potting material. A backplane and flex cables provide electrical interconnection between modules and external interfaces for system initialization. All modules are constructed using MCM-L technology, where unencapsulated silicon

chips are attached to multilayer laminated circuit boards. Chip resistors, capacitors, and bare integrated circuit die are attached to the circuit board using conductive epoxy. A combination of aluminum wire bonds and conductive epoxy are used for electrical connections. This module assembly process does not preclude the use of prepackaged integrated circuits, but bare dies are used to attain the highest density circuit construction. The modules are over-molded with epoxy to provide mechanical and environmental protection and assist with thermal management. Modules fabricated in this manner have survived centrifuge tests in excess of 30,000 g and more than 400 thermal shocks from -55°C to +125°C. The modules are integrated into the G&N electronics by soldering pins into a backplane.

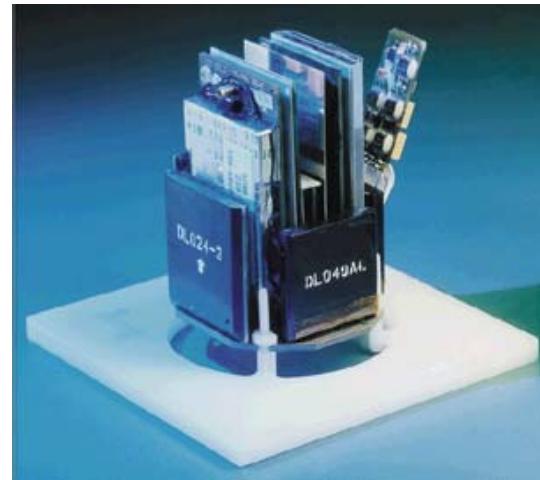


Figure 5. CMATD Electronics Assembly

The CMATD Program culminated in flight tests of three projectiles at Yuma Proving Ground on August 3, 1999, August 5, 1999, and February 2, 2000. All projectiles were launched at a setback acceleration of approximately 6500 g with initial velocities of approximately 2200 ft/s (670 m/s).

The initial flight tests demonstrated survivability of the overall projectile design and subsystem functionality and performance. From the telemetry data acquired from the first two flights, all six MEMS instruments survived the gun launch and operated as expected and provided accurate in-flight measurements. The lessons learned in these test flights regarding the control actuation system (CAS), roll control software, and launch signal subsystems were modified for the third projectile. Test Flight 3 was conducted February 2, 2000, and the GN&C system survived gun launch and all systems operated. GPS was reacquired successfully at 31 seconds after launch and the closed-loop guidance, navigation, and control executed as designed.

2.3 MMIMU

The Special Projects Office of the Defense Advanced Research Projects Agency (DARPA) and the Air Force Research Laboratory (AFRL) sponsored Draper Laboratory in 2000 to develop and demonstrate the world's highest performance MEMS IMU, the DARPA MMIMU (Ref 9). The performance requirement is a 10 deg/h, 500 μ g IMU with a performance goal of 1 deg/h, 100- μ g, and with a unit production cost goal of \$1200. Designed as a low-cost, smaller, low power alternative to Honeywell's ring laser gyro-based tactical-grade HG1700 IMU, the MMIMU is 2.7 inches (68.5 mm) in diameter and 1.4 inches (35.5 mm) high (8 in³) with a weight of 260 grams. The IMU is designed to perform over a temperature range of -40 to +85°C and consume less than 3 W.

Development experience and the need to design for ease of manufacture and low cost drove the MMIMU designs to much simpler implementations. The MMIMU assembly shown in Figure 6 features a set of four plug-in modules with screw attachments. From top to bottom are the IMU processor, power conversion electronics (PCE), accelerometer, and gyro modules. Each module consists of a PCB mounted to a Kovar frame, and alignment pins are used to guide module-to-module assembly and connector mating. Top and bottom seam-welded covers provide a hermetically-sealed system.

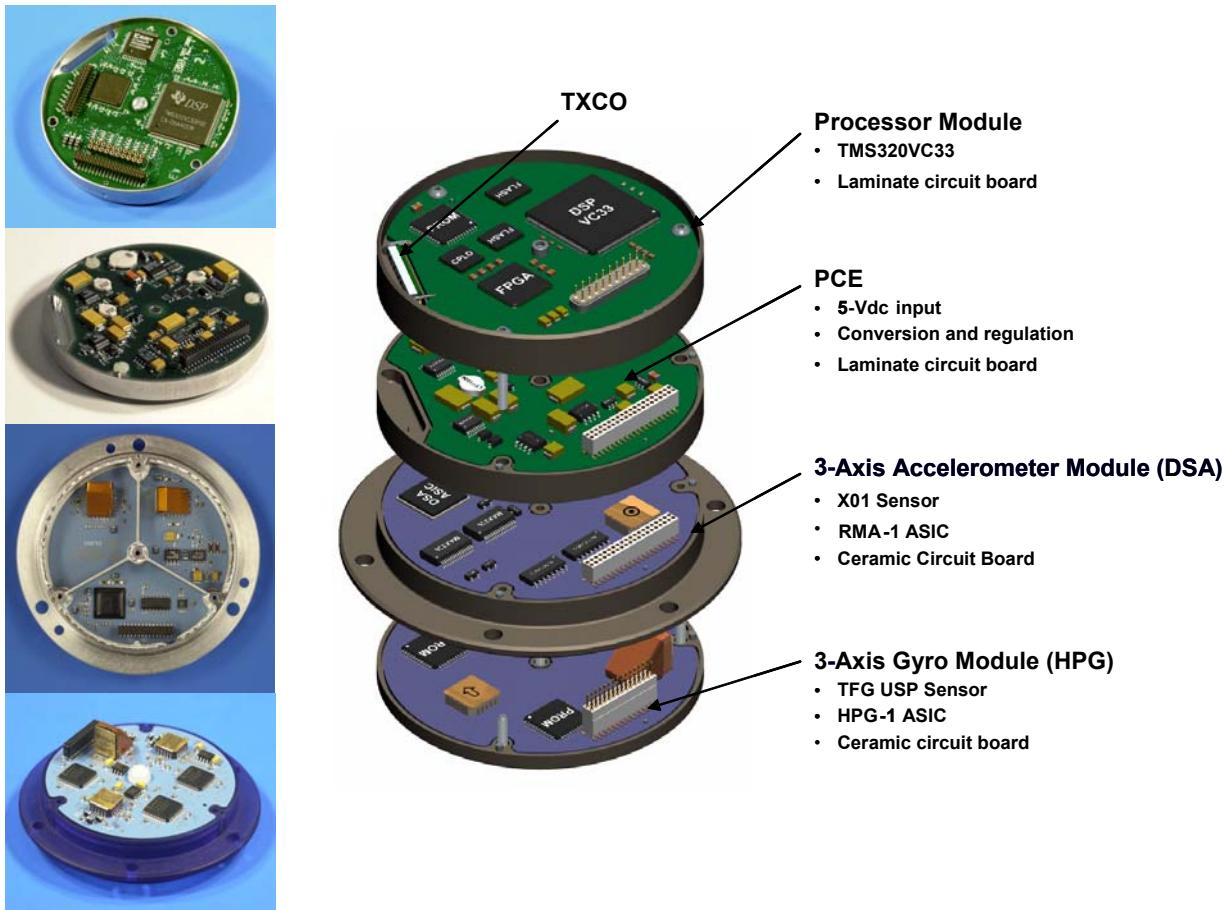


Figure 6. MMIMU Assembly

To meet the volume constraints, a novel planar stacked disk approach was developed for system packaging. Inertial sensors are hermetically sealed in an leadless ceramic chip carrier (LCCC). A separate 3-axis accelerometer and 3-axis gyroscope instrument module are configured with ASIC electronics, further improved to reduce the number of off-chip components. The two 3-axis inertial instrument modules contain the latest MEMS TFG and pendulous accelerometer sensor designs. Sensors are hermetically sealed in 20-pin LCCC packages and are mounted in an orthogonal configuration on each low-temperature co-fired ceramic (LTCC) circuit board. Ceramic mounting blocks are employed for the orthogonal set, and a separate mixed-signal CMOS ASIC in a chip-scale package operates each sensor.

ASIC electronics implemented in CMOS processes provide excellent performance at low power and cost, while enabling the small size objectives to be met. Much of the gains in performance experienced in TFG development are directly attributable to the ASIC electronics. The MMIMU gyro ASIC, the High-Performance Gyro digital ASIC (HPG-1), was developed under the DARPA MMIMU Program. This third-generation ASIC uses a high-speed $\Sigma-\Delta$ converter to acquire the gyro rate information directly from the preamplifier. All sense axis processing is performed digitally, eliminating errors associated with drift in the baseband electronics while achieving dynamic ranges in excess of 140 dB. The accelerometer electronics form a differential capacitive measurement system consisting of a carrier signal generator and demodulator

circuitry providing a DC output proportional to acceleration. During closed-loop operation, control compensation and rebalance drive circuitry are added. An existing second-generation analog ASIC (RMA-1) was used for the accelerometer. The ASICs were packaged in custom ball grid array packages.

Table 2. MMIMU Sensor Performance

Parameter		Gyros		Accelerometers	
		Goal	Actual	Goal	Actual
Bias Turn-on Repeatability	deg/h or mg	1 (1 σ)	3 (1 σ) ⁽¹⁾	0.5	2 (1 σ) ⁽¹⁾
Bias In-run Stability	deg/h or mg	1 (1 σ)	5 (1 σ) ⁽²⁾	0.1 (1 σ)	1 (1 σ) ⁽²⁾
Bias Drift	deg/h or mg		5 (1 σ) ⁽³⁾		2 (1 σ) ⁽³⁾
Scale Factor Turn-on Repeatability	ppm	140 (1 σ)	70 (1 σ) ⁽¹⁾	210	125 (1 σ) ⁽¹⁾
Scale Factor In-run Stability	ppm	140 (1 σ)	100 (1 σ) ⁽²⁾	210	600 (1 σ) ⁽²⁾
Axis Misalignment	mrad	0.5	1	0.5	1
Input Axis Repeatability	mrad	0.1	0.2	0.1	0.2
Maximum Input	deg/s or g	1,000	1,000 ⁽⁴⁾	50	45 ⁽⁴⁾
Bandwidth	Hz	150	150 ⁽⁴⁾	100	100 ⁽⁴⁾
Angle Random Walk	deg/ \sqrt{h} or m/s/ \sqrt{h}	0.030	0.050	0.035	0.02

Notes: (1) Turn-on to turn-on over 0°C to +70°C, power-down, and mount/dismount, 14 days

(2) Post-compensation over 0°C to +70°C

(3) RSS of turn-on and in-run performance

(4) Typical; other ranges available

Electronic components are surface mounted with solder and conformal coated with no module or system-level potting. Analysis has shown that combinations of die attach adhesive and a rigid structural frame are adequate to support the PCB module stack under loads applied during launch. Vibration isolation is an integral part of the mounting plate and can be customized for specific environments by the end user.

Build of two MMIMUs was started, with one completed and tested by August 2002. Table 2 presents a summary of the MMIMU goals and the actual IMU test data. These results represent the highest published performance data attained to date on an all-Silicon MEMS IMU. The DARPA MMIMU Program was the culmination of three years of focused development on advancing the performance of MEMS gyroscopes. This effort leveraged 10 years of development and over \$100M of Draper IR&D and government investments in the development of MEMS inertial technology.

2.4 LCGEU INS/GPS

The US Navy initiated an investigation into providing alternate guidance electronic unit technology to address survivability across gun-shocks and enable a significantly lower unit production cost. The LCGEU program's goal was to develop a gun-hard, low cost INS/GPS system using COTS inertial sensors and other COTS

components (Ref 7). The LCGEU is designed to be modular so as to fit into various airframes. It is a 20 cu in (328 cc) system, hardened to 18,000g, and has deep integration software for enhanced GPS anti-jam capability. It was successfully tested in long range guided flights in the Ballistic Trajectory Extended Range Munition (BTERM) in September 2003 and in the EX-71 Extended Range Guided Munition (ERGM) in October 2003.

2.5 CGIMU

The goal of the Army's Common Guidance IMU program is to develop a new system that extends the capabilities of the previous systems further yet in terms of highest performance with high launch loads, anti-jam GPS, decreased volume, and low production cost (\$1200 per IMU and \$1500 per INS/GPS in high volume) (Ref 10). Honeywell, in partnership with Draper Laboratory, was funded in 2001 to develop a common system for use in the majority of the Army's, Navy's, and Air Force's tactical weapons. Significant development effort was planned within the scope of this program to further increase sensor performance while reducing packaging volume and overall system cost. Honeywell's program draws significant leverage from previous developments. The MMIMU technology was the baseline for Phase 1 of the CGIMU. The final result of this program is expected to provide a producible production-ready qualified system for guided tactical weapons. Figure 7 outlines Honeywell's Common Guidance technology progression.



Figure 7. Common Guidance Technology Progression

3. KEY TECHNOLOGY DEVELOPMENTS

Performance for gun-hard munitions must be maintained through all environments, including high-g launch shock in excess of 20,000 g, a wide temperature range of -54°C to +125°C, and also over a 20-year duration, a time period typically identified for fielded systems. System deployment must be achieved with requisite reliability and without maintenance. Achieving the requisite inertial performance across the combination of environments are the principal challenges facing MEMS technology. This section describes some of the key technology developments for low-cost, gun-hard systems.

3.1 Sensors

The TFG is a proven design for high-g applications and has undergone many design iterations and incorporated many performance-enhancing features to ease fabrication and increase performance (Ref 11). Performance data indicate that the TFG currently performs at levels in the 10 to 50 deg/h range (3 σ) over temperature ranges of -40°C to 85°C for many months time and shock inputs of up to 12,000 g. The companion accelerometer sensor is a pendulous mass displacement device manufactured using a similar dissolved wafer SOI process. An unbalanced proof mass plate is suspended by torsional spring flexures in a

see-saw type configuration. Proof mass and flexure design variations yield devices with full-scale ranges from 1 to 100,000 g.

Trades and analyses conducted under the DARPA MMIMU program indicate that the optimal gyro performance is achieved at a thickness of between 50 and 100 μm . Continued evolution of advanced processes to build thicker, more 3-dimensional parts that are less susceptible to fabrication tolerances is critical to the performance and cost targets.

Major advances in sensor design and fabrication included development of in-plane accelerometers (IPAX), out-of-plane gyroscopes (OPG), and in-plane gyroscopes with an upper sense plate (USP) pick-off. The USP design is required to provide a higher signal-to-noise ratio and improve performance during vibration inputs. IPAX and OPG sensors allow planar mounting of sensors to further minimize overall system packaging volume. Working devices of two TFGs and one OPG on one chip, and two IPAXs and one out-of-plane pendulum accelerometer on another single chip have been demonstrated under DARPA/US Army AMCOM funding. These are necessary for IMUs smaller than 2 cu. in. (33 cc), and further development is required to perfect these chips.

3.2 IMU System Architecture

The evolution of ASIC electronics is critical to furthering the performance and miniaturization of MEMS systems. Varying mission needs are readily accommodated by versatile electronic configurations adapted for specific requirements. Figure 8 depicts the IMU system architecture evolution from ERGM Demonstration through MMIMU. Each stage represents an order of magnitude improvement in performance. Continued development of digital ASIC electronics with hard-wire signal processing is required to realize the cost, performance, and size objectives for an all-digital IMU architecture.

3.3 GPS Receiver Technology

Although this paper deals primarily with MEMS development, the importance of GPS in realizing performance and size needs to be mentioned. GPS technology is also required to continually evolve in terms of miniaturization, performance, and cost. Primary GPS requirements for competent munition applications include low power, small volume, high-g survivability and fast reacquisition of GPS after barrel exit. The need for rapid reacquisition imposes the need to precisely maintain the GPS clock frequency reference across the shock event.

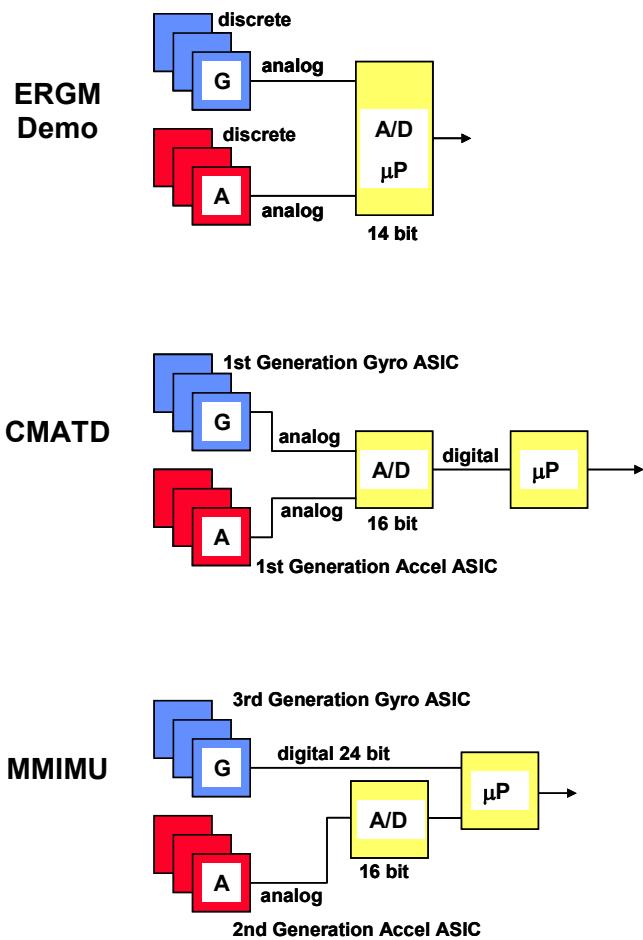


Figure 8. IMU System Architecture Evolution

Maintaining GPS lock against both intentional and non-intentional jamming is a critical requirement growing in importance. Because of the inherent accuracy in weapon systems employing GPS, much work is being performed in developing methods of denying GPS availability. Various techniques are employed to boost the resistance of GPS to these jamming technologies. In addition to antenna noise cancellation, hardware filters, enhanced signal processing, body shading, and antenna null techniques currently employed, methods for deeply integrating (Refs 12 and 13) the INS/GPS systems are also under development. These deep integration algorithms employ unique filters to optimally blend the inertial and GPS information and control the code and carrier tracking performance of the receiver. By narrowing the tracking bandwidths during high jamming, additional immunity and loss of lock performance is obtained. Deep integration techniques are most poised to take advantage of the low-cost inertial and GPS systems and become a generic capability within the INS/GPS technology.

3.4 Sensor and System Packaging

High-g requirements presented significant packaging challenges to minimize the size and cost of a product expected to last 20 years in an uncontrolled environment. Typical requirements include a 20,000-g setback acceleration, angular rates up to 250 revolutions per second, and a 5000-g set-forward acceleration upon exit from the gun barrel. Experience to date suggests electronic assemblies survive gun launch provided they are properly mounted. Shock mounts are typically employed for inertial components to attenuate and dampen the high-g launch loads and in-flight vibration inputs.

Micromechanical inertial instruments were initially automotive-based designs repackaged for high-g applications. ERGM Demonstration packaged these automotive MEMS sensors and ASICs in standard thick-film hybrid hermetic packages mounted to multilayer epoxy glass laminate printed circuit boards (PCBs). CMATD combined higher performing sensors, second-generation ASIC electronics, and multilayer multichip module-laminate (MCM-L) PCBs. Current generation instruments use more advanced ASIC electronics that eliminate virtually all off-ASIC components.

Future IMUs for gun-launched projectile applications require decreasing the volume of the MMIMU by a factor of 4. The inertial instrument modules dominate the current size of the MMIMU design. To minimize development time and cost, commercial field programmable gate arrays (FPGAs) were used for many digital functions. Future designs package improved ASICs with configurable gate arrays (CGAs) to replace FPGAs, and passive conditioning electronics into a custom ball grid array (BGA) package. Using CGAs, the current MMIMU board diameter is reduced from 2.6 inches (66 mm) to 1.8 inches (46 mm), yielding a 50% volume reduction.

Three-axis measurements are achieved by rotating sensor packages on ceramic mounting blocks. Further size reductions are achieved using off-axis sensors for orthogonality. Inertial input axes are typically fixed by the design and mounting of the sensor in the three-axis instrument module. The pendulous accelerometer sensor measures acceleration normal to the module circuit board, while the TFG measures rotations in the plane of the circuit board. By using the new OPG and IPAX sensor devices, ceramic mounting blocks are eliminated and the heights of individual modules are greatly reduced. Utilizing a combination of these new sensor technologies and the aforementioned ASIC electronic advances with CGA devices custom packaged in a BGA format enables the realization of a complete 6-axis inertial instrument module, thus yielding an additional 50% volume reduction. Figure 9 illustrates the size reduction advantages of using these latest packaging techniques.

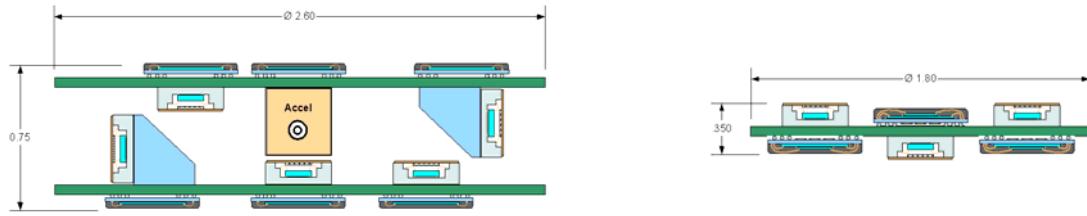


Figure 9. MMIMU 3-Axis Sensor Modules vs. later OPG and IPAX 6-Axis Sensor Module

4. CURRENT MEMS IMU DEVELOPMENTS

As of today, MEMS IMUs have been successfully demonstrated in numerous applications, including the high g applications (e.g., artillery shells, extended range (rocket assisted) munitions, mortar shells, anti-tank weapons) mentioned previously. MEMS IMUs can be purchased for commercial and military uses from numerous companies (e.g., Honeywell International's HG1900, HG1930, and HG1940 (through Integrated Guidance Systems), Atlantic Inertial Systems' SiIMU02, SiIMU04, and SiNAV (Refs 14 and 15), LITEF's μ IMU (Ref 16), Systron Donner's MMQ50 (Ref 17) and SDI500 quartz sensor IMUs, Gladiator Technologies' Landmark20 eXT and MRM10, Miltec's Mini3x). A MEMS inertial reference unit has been deployed in space for attitude control of an Inertial Stellar Compass. The automotive industry is the second biggest MEMS market world-wide with low-cost, low-performance gyroscopes and accelerometers being one of the main applications (Ref 18).

Several efforts on performance improvement are ongoing. One such area is MEMS for personal navigation/personal positioning; the major problem being the intermittent availability or complete denial of GPS. Another performance improvement initiative is the DARPA BAA started in 2004 for navigation grade MEMS gyros. Also, the European Space Agency (ESA) has funded several market analyses and feasibility studies (Ref 19) based on European developments of MEMS gyros by companies such as BAE SYSTEMS (UK), Bosch (Ger), EADS CRC (Ger), Litef (Ger), Sagem (Fr), SensoNor (Norway), and Thales (Fr). Desired goal is around 0.1 deg/h bias stability. Quartz IMUs also continue to show improved performance in several areas. Systron Donner's MMQ50 series combines a quartz rate sensor with a silicon MEMS accelerometer. The quartz rate sensor is based on technology developed for the automobile industry to which over 25 million have been shipped to date. Systron Donner continues to develop more accurate and robust sensors for future products (Ref 17). Also, ONERA (Fr) continues development of the VIA (Vibrating Inertial Accelerometer) and the VIG (Vibrating Integrating Gyro) (Ref 20). The VIA's accuracy is currently around 300 micro g. A further reduction in size, with targeted accuracy of 100 micro g, is underway by configuring the accelerometer on one single chip rather than two.

Gimbaled MEMS systems is another technique used to enhance the performance of MEMS IMUs (Ref 21). The incorporation of miniature gimbals has also been shown to produce performance improvements by an order of magnitude by allowing periodic calibration and alignment. Another technique to achieve performance, especially over high dynamic range, is to use controlled arrays of MEMS sensors. This was used in the development of guided artillery shells (Ref 1). More recently (Ref 22), results from a three year US Army component development program that investigated multiplexed COTS and custom accelerometer arrays, have demonstrated two orders-of-magnitude increase in dynamic range. Also shown was that the integration on the same chip of an angular rate sensor with an accelerometer array and temperature sensors improved gyro compensation for vibration and thermal effects. Co-location of several devices on the same chip is expected to reduce size significantly, but probably only with marginal performance gains.

5. THE FUTURE

The vision for far future inertial MEMS reflects a radical departure from the systems discussed in this paper. Wafer-scale integration of high-performance planar array sensors, with multi-channel digital ASICs and multi-axis on-chip sensors, will create complete systems on a chip, offering a further order of magnitude reduction in volume. Using high-volume foundries, these tactical-grade instruments will thereafter be reduced to commodity items and installed as chip sets in higher-level systems. Future INS/GPS system designers will be able to select inertial and GPS chip sets with desired performance attributes out of catalogs in the same manner that an analog circuit designer selects operational amplifiers today.

In addition to the needs described for competent munitions, commercial applications will evolve to take advantage of the higher performance afforded by these technologies. Self-locating cell phones, intelligent vehicle highway systems, personal navigation, and autonomous control are all applications poised to integrate these technologies and exploit its utility. Personal navigation in areas where GPS is unavailable is of particular interest and is a very active research area. Analogous to the proliferation of GPS into common life, once these technologies are available, the engineers and designers closest to the problems will find techniques to employ singular or integrated aspects of these technologies to address the needs.

ACKNOWLEDGEMENTS

This paper is an update of a paper presented at NATO Lecture Series SET-064 in October 2003 and May 2004 and Lecture Series SET 116 in October/November 2008 and March 2009.

REFERENCES

- [1] Gustafson, D., R. Hopkins; N. Barbour and J. Dowdle, *A Micromechanical INS/GPS System for Guided Projectiles*, ION 51st Annual Meeting, Colorado Springs, CO, June 5-7, 1995
- [2] Dowdle, J. and K. Flueckiger, *An Integrated GPS/Micromechanical IMU for Navy 5" Projectiles*, The Institute of Navigation Conference, Cambridge, MA, June 18-20, 1996
- [3] Connelly, J., and G. Brand, *Advances in Micromechanical Systems for Guidance, Navigation, and Control*, AIAA Guidance, Navigation and Control Conference, New Orleans, LA, 11-13 August 1997
- [4] Gai, E., *Guiding Munitions with a Micromechanical INS/GPS System*, 4th St. Petersburg Conference on Integrated Navigation Systems, St. Petersburg, Russia, May 1998
- [5] Kourepinis, A., J. Borenstein, J. Connelly, R. Elliot, P. Ward, M. Weinberg, *Performance of MEMS Inertial Sensors*, 24th Joint Services Data Exchange Conference, Anaheim, CA, November 16-20, 1998
- [6] Anderson, R., D. Hanson, and A. Kourepinis., *Evolution of Low-Cost MEMS Inertial System Technologies*, ION GPS 2001, Salt Lake City, UT, September 11-14, 2001
- [7] Coskren D., Easterly T., and R. Polutchko, *Low-Cost GPS/INS Guidance for Navy Munitions Launches*, GPS World, Vol 16, Issue 9, September 2005
- [8] Brown, T., B. Davis, D. Hepner, J. Faust, C. Myers, C. Muller, T. Harkins, M. Holis, and B. Placzankis, *Strap-Down Microelectromechanical (MEMS) Sensors for High-G Munition Applications*, 10th Electromagnetic Launch Technology (EML) Symposium, San Francisco, CA, 25-28 April 2000. Journal: IEEE Transactions on Magnetics, vol. 37, no. 1, pt. 1, p. 336-42, January 2001

- [9] Sitomer, J., J. Ha, A. Kourepinis and J. Connelly, *High-Performance MEMS Inertial Measurement Unit (MMIMU) for Tactical Applications*, IEEE PLANS 2002, Palm Springs, CA, April 2002
- [10] Warnasch A., and A. Killen, *Low-Cost, High G, MEMS IMU Program*, IEEE PLANS 2002, Palm Springs, CA, April 2002
- [11] Connelly, J., A. Kourepinis, and T. Marinis, *Micromechanical Sensors in Tactical GN&C Applications*, AIAA Guidance, Navigation and Control Conference, Monterey, CA, August 5-8, 2002
- [12] Flueckiger, K., *A High Anti-jam MEMS-Based INS/GPS Navigator*, Proceedings for the 26th Joint Services Data Exchange (JSDE) for Guidance, Navigation, and Control Symposium, October, 2000
- [13] Gustafson, D., J. Dowdle, and K. Flueckiger, *A High Anti-jam GPS-Based Navigator*, The Draper Technology Digest, Vol. 5, pp. 4-13, 2001
- [14] Sheard K., et al, *Gun Hard MEMS Sensor and Integrated Navigation Technology for Precision Guidance Applications*, NATO RTO SET-114 Symposium, Antalya, Turkey, October, 2007
- [15] Habibi S., Coopert S., Stauffer J-M., and B. Dutoit, *Gun Hard Inertial Measurement Unit Based on MEMS Capacitive Accelerometer and Rate Sensor*, IEEE/ION PLANS 2008, Monterey, CA, May, 2008
- [16] Geiger W. et al, *MEMS IMU for AHRS Applications*, IEEE/ION PLANS 2008, Monterey, CA May 2008
- [17] Jaffee, R., Ashton, T. Madni, A., *Advances in Ruggedized Quartz MEMS Inertial Measurement Units*, Position, Location, And Navigation Symposium, IEEE/ION, Coronado, CA, April 2006
- [18] www.wtc-consult.de, *Think Small Feature Articles: Prospects for MEMS in the Automotive Industry*, July 2007 and *Taking the Pulse of the MEMS Industry*, April 2007
- [19] Dussy S. et al, *MEMS Gyro for Space Applications – Overview of European Activities*, AIAA GN&C Conference and Exhibit, San Francisco, CA, August 2005
- [20] Le Traon O. et al, *A New Quartz Monolithic Differential Vibrating Beam Accelerometer*, EEE/ION PLANS 2006, Coronado, CA, April 2006
- [21] Ash M. and Martorana R., U.S. Patent 6,778,908 - August 2004; U.S. Patent 6,895,678 - May 2005
- [22] Hudson T., et al, *Multi-Sensor Inertial Array Technologies for Advanced Microsystems*, IEEE/ION PLANS 2006, Coronado, CA, April 2006

